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16. ABSTRACT The paper describes a flux force/condensation (FF/C) scrubbing system that was built to control particulate emissions from a secondary metals recovery furnace. Total mass penetration and fractional penetration measurements were made under several different operating modes. The performance of the demonstration scrubber was consistent with the results of previous studies on FF/C scrubbing. The system was generally capable of 90-95% efficiency on particles with a mass median aerodynamic diameter of 0.75 microamps. This efficiency was achieved with a 68 cm (27 in.) W.C. gas-phase pressure drop.

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Scrubbers	Furnaces	Stationary Sources	07A,13I	13A
Flux Density	Insulated Wire	Flux Force/Condensation Scrubber	14G	09A
Condensing	Copper		07D	07B
Dust	Wire	Particulate	11G	
Aerosols		Metals Recovery		

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FF/C Scrubber Demonstration on A Secondary Metals Recovery Furnace

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A flux force/condensation (FF/C) scrubbing system was built to control particulate emissions from a secondary metals recovery furnace. Total mass penetration and fractional penetration measurements were made under several different operating modes. The performance of the demonstration scrubber was consistent with the results of previous studies on FF/C scrubbing. The system was generally capable of 90 to 95% efficiency on particles with a mass median aerodynamic diameter of 0.75 μA. This efficiency was achieved with a 68 cm (27 in.) W.C. gas-phase pressure drop.

Flux force/condensation (FF/C) scrubbing can achieve high efficiency fine particle collection at lower power input than the conventional high-energy scrubbing systems. FF/C scrubbing effects are generally caused by contacting hot humid gas with colder liquid and/or by injecting steam into saturated gas. First, the transfer of water vapor toward the cold surface sweeps particles with it: this effect is referred to as diffusiophoresis. In addition, the condensation of water on the suspended particles causes the particle size to increase. The resultant particles are easier to collect by inertial impaction after growth has occurred by condensation.

The demonstration scrubber described in this paper was part of an R&D sequence supported by EPA contracts.[1-5] The basic theory and potential applications of FF/C scrubbing were treated in the scrubber systems study and reported in the "Scrubber Handbook".[1] The feasibility of FF/C scrubbing was evaluated in the next contract program[2] which covered the development of mathematical models for predicting its efficiency and bench scale laboratory work for experimental verification. This was followed by two pilot plant studies: first of a 14 m^3/min (500 cfm) multiple sieve plate column with provisions for steam addition and water cooling,[4] and second of a 28 m^3/min (1000 cfm) horizontal spray scrubber with water cooling.[5] The object of the demonstration program described in this paper was to test an FF/C scrubbing system on an actual industrial source.

Source Information

A secondary metals recovery furnace was selected for control in the demonstration. The source operation, ranked among the top 15 particulate sources in the Midwest Research Institute particulate system study,[6] involved the burning of insulation from scrap copper wire.

The operator loaded metal pallets covered with randomly coiled scrap wire into a preheated gas-fired furnace. The charging door was closed, and as the insulation got hot, it melted and burned. Dense black smoke containing hydrochloric acid, metal chorides, and other components was emitted through a breeching into the first of two gas-fired afterburners. Because of the batch loading and the variable emissions as the insulation burned away, the particulate emission rate was very cyclic. Opacity was high during the first several minutes and gradually decreased over the 30 min operating cycle.

FF/C Scrubber System

The scrubbing system was composed principally of a cross-over duct from the furnace stack, a spray type quencher, a sieve plate column scrubber, and a spray type cooling tower. The FF/C scrubber system is shown schematically in Figure 1. (Table I describes the process streams.)

FF/C Process Description

A maximum flow of 200 Am^3/min (7000 acfm) of flue gas flowed from the afterburner stack through a 9.1 m (30 ft) long crossover duct to a spray quencher. The gases were preconditioned in the crossover duct and the quencher by circulating water sprays to reduce the volume and to saturated the gases with moisture. From the quencher the gas flowed to a multiple plate column, where it was contacted with a cooled solution of Na_2CO_3, and the particles were grown and collected by a combination of diffusiophoresis and inertial impaction. The gas flowed from the scrubber through an entrainment separator into the induced draft fan, and then to the exhaust stack.

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Mechanical Design

A 9.1 m (30 ft) long crossover duct and associated supporting truss were built from the furnace stack to the FF/C scrubbing system. Because of the high temperature and the need to conserve gas enthalpy, the duct had to be insulated. During the program the carbon steel duct corroded and was replaced with a type 316 S.S. duct. Several spray nozzles were also installed to introduce a Na_2CO_3 solution for cooling and to reduce corrosion.

for the pilot study, but it was much larger and more complex than would be required for ordinary use. As tested, the scrubber unit incorporated several combinations of plates with 0.48 cm (3/16 in.) and 0.32 cm (1/8 in.) diameter perforations. The scrubber entrainment separator was a tube bank with ten rows of 1.3 cm (1/2 in.) diameter tubes in a series.

Scrubber liquid was cooled by spraying into the upper part of a forced draft tower. A spray tower was used rather than a packed (or filled) tower because of a concern for solid deposition. Air was drawn upward through the tower by a propeller

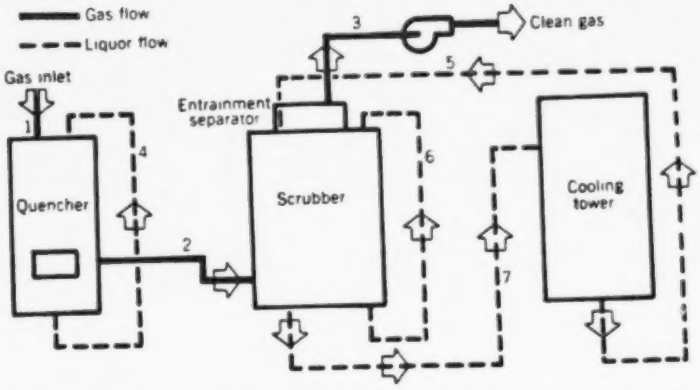

Figure 1. Flow diagram of FF/C scrubbing system. (See Table I for description of numbered process stream.)

The quencher included a 1.52 m (5 ft) diameter and 3.7 m (12 ft) long vertical spray chamber with cocurrent gas/liquid contact. The quencher had a type 316 S.S. shell, spray nozzles, and heater piping. The external piping of the quench unit was CPVC (chlorinated polyvinyl chloride), and the gas duct to the scrubber was Fiberglas-reinforced plastic (FRP). The FRP duct held up well during the program. A bed of 2.54 cm (1 in.) polypropylene pall rings was used as an entrainment separator and placed at the bottom of the quencher, upstream of the outlet, to minimize entrainment to the plate scrubber. While only a few percent of the rings were heat deformed during the 4 months of operation, this design would not be satisfactory without positive means for keeping the packing wet.

FF/C scrubber consisted of a cylindrical 2.3 m (7.5 ft) and 3.0 m (10 ft) high, five-plate structure with provision for locating a sixth plate in a split tower design (see Figure 2). The plate scrubber was a hybrid design which offered flexibility in the mixing of sprays and plates, in the number of plates, and in the points of liquid introduction. The design was desirable

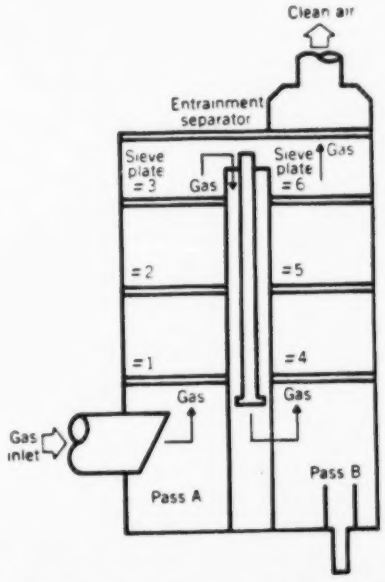

Figure 2. Scrubber unit of FF/C demonstration plant.

fan, which was located above an entrainment separator. Special attention was given to the design of and provision for a high efficiency entrainment separator which was required because of the fine spray developed in the tower. The unit consisted of three rows of wave plate baffles with spacing of 1.3 cm (1/2 in.) and a wave amplitude of 2.2 cm (7/8 in.). Baffle rows were offset 0.65 cm (1/4 in.) and baffle direction in each row was reversed. The cooling tower piping was PVC, the spray nozzles were 316 S.S., and the sump tank was polyethylene.

Table I. Process streams for FF/C scrubber system at metals recovery furnace.

Stream no. (See Fig 1)	Composition	Temp °C	Vol. flow Am/min (G) or l/min (L)	Mass flow kg/hr	Enthalpy (0°C Base) kcal/kg	y g water / g d. gas
1	Flue Gas	649	198	4,400	226 (d.g.)	0.07
2	Gas Mixture	71.7	100	5,384	211 (d.g.)	0.31
3	Gas Mixture	50.6	71.8	4,480	67.5 (d.g.)	0.09
4	Water	59.4	59.0	3,540	59.4	...
5	Water	40.6	568	34,100	40.6	...
6	Water	59.4	568	34,100	59.4	...
7	Water	59.4	568	34,100	59.4	...

The induced draft fan for the scrubbing system was a 25 hp, belt-driven blade type, capable of 142 m^3/min (5000 scfm) at 56 cm (22 in.) W.C. pressure. In some of the experimental runs, the fan capacity was augmented to give 69 cm (27 in.) W.C. pressure.

Instrumentation was provided to measure:

1. Flow rate.
2. Temperature.
3. Pressure.
4. Humidity.
5. Particulate mass loading.
6. Particle size distribution.
7. Gas composition.

These parameter measurements were made to define both the performance and the process conditions at different locations of the scrubber system during the test program.

Liquor System

Water from the quencher was drained to a holding tank and recirculated to the quencher inlet. Liquor from the scrubber was collected in another tank and sprayed into the cooling tower. The cold outlet liquid from the cooling tower was then recirculated to the scrubber. The demonstration plant was operated in compliance with liquid disposal requirements obtained from local authorities. The major requirements were that the liquid discharge to the sewer be neutralized and that it not interfere with the sewage treatment plant processes. The liquor was treated periodically and the pH was controlled with soda ash.

Experimental Results and Discussion

The scrubber system was operated for about 4 months under several different modes. The purpose of the testing phase of the program was to obtain the overall mass efficiency of the system, the particle collection efficiency across the FF/C scrubber, the operational reliability of the demonstration plant, and the economics of FF/C scrubbing.

Results

The FF/C demonstration plant was evaluated with several combinations of plate configuration, scrubber liquid flow arrangement, quenching, and sodium carbonate use. A major division of the experimental measurements can be made by grouping the runs before the crossover duct corroded out and those after the new duct was installed. This division is significant not only because the duct was replaced but also because additional sprays were installed in the duct, an additional plate was added in the scrubber unit, and fan pressure capacity was augmented by a booster blower.

Table II. Chemical analysis of particulates at secondary metals recovery furnace.

Atomic absorption analysis, %	
Cu	11.2
Fe	8.3
Na	6.3
Pb	22.6
Zn	1.8

The chemical nature of the effluent was determined by atomic absorption. The particulate filter catch was composed of metals and halogens; the impinger catch showed a high concentration of hydrochloric acid (see Tables II and III). In the runs where fluorinated polymer insulation was present in the scrap, hydrofluoric acid was encountered. Because of the very high halogen acid concentration, a basic addition to the scrubber liquor and corrosion resistant materials were used. For some particle size distribution sampling, Teflon cascade impactors were used.

Total mass penetration was measured for all runs and fractional penetration was measured for selected runs. The latter is penetration related to particle diameter and was computed from cascade impactor inlet and outlet particle size distribution data.

Table III. Chemical analysis of impinger solution at secondary metals recovery furnace.

Component	mg/l	wt %
Cl^-	6370	85.3
SO_4^{-3}	136	1.8
NO_3^-	93	1.2
Zn	390	5.2
Fe	240	3.2
Cu	85	1.1
Pb	60	0.8
Si	73	1.0
Ca	17	0.2

Overall penetration in an FF/C scrubber depends on particle size distribution, scrubber design, pressure drop, particle number concentration, particle composition, and the mechanism by which condensation occurs. Consequently Figure 3, a plot of penetration versus condensation ratio, is subject to many qualifications. Condensation ratio is the ratio of grams of water condensed per gram of dry gas. In Figure 3, the two curves show the penetration versus condensation results from a previous pilot plant study on FF/C scrubbing; the data points show some of the overall penetration data from the demonstration scrubber. Penetration decreases with condensation ratio, and system performance was better after the new duct was installed and other modifications were made. The data points represented by the triangles were taken while the old duct was in place, and the data points represented by the circles were taken after the new duct was installed.

Fractional penetration characteristics are shown in Figures 4 and 5. It is important to note that these are for a given scrubber design, pressure drop, condensation ratio, and particle number concentration. The figures show the experimental penetration curves and those predicted by a design model. Figure 4 shows a case where the fit between experiment and prediction is excellent; the fit of Figure 5 is not so good. In general, the match between performance and prediction is good and definitely adequate for design purposes.

Performance

The system was generally capable of about 90 to 95% efficiency on particles with a mass median aerodynamic diameter of 0.75 μmA (about 0.3 μm physical diameter for particles with a density of 4.0 g/cm^3). This efficiency was achieved with a 68 cm (27 in.) W.C. gas-phase pressure drop. A conventional high energy scrubber without FF/C effects would require a pressure drop of roughly 250 cm (98 in.) W.C. for 90% particle collection efficiency (σ_g = 2.5).

Economics

In order to compare an FF/C scrubber system with a conventional high energy scrubber, knowledge from the demon-

stration study was used to refine the FF/C scrubber design. A cost estimate was made for this design and compared to a parallel design and cost estimate for a conventional high energy system. It is important to note that the high concentration of acid gases required both mass transfer and particle collection capability.

The refined FF/C system design includes:

1. Scrap: premiun No. 1 wire
2. Efficiency: 88% by mass
3. Inlet particle size distribution:
   a. mass median diameter = 0.75 μmA
   b. standard deviation = 2.5
4. Pressure drop: 70 cm (28 in.) W.C.
5. Equipment:
   a. saturator
   b. condenser
   c. venturi
   d. entrainment separator
   e. cooling tower

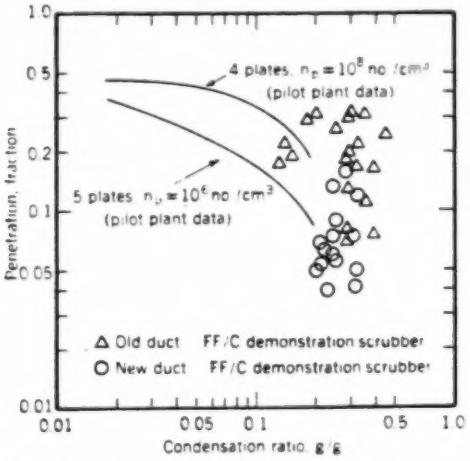

Figure 3. FF/C demonstration scrubber performance.

The control of furnace emissions from the incineration of premium No. 1 wire would require 88% collection efficiency and a scrubber pressure drop of about 70 cm (28 in.) W.C. Since high mass transfer efficiency is required to control the acid gases, the total combination of saturator, condenser, scrubber, and entrainment separator must be included in the design. A venturi scrubber appears to be the best choice for particle collection after condensation and growth have occurred in the condenser. Because the mass transfer capability of a venturi and entrainment separator is limited, the saturator and condenser must be efficient for gas absorption.

The high energy scrubber system design features include:

1. Scrap: premiun No. 1 wire
2. Efficiency: 88% by mass
3. Inlet particle size distribution:
   a. mass median diameter = 0.75 μmA
   b. standard deviation = 2.5, dimensionless
4. Pressure drop: 240 cm (94 in.) W.C.
5. Equipment:
   a. saturator
   b. condenser
   c. venturi
   d. entrainment separator

The conventional high energy system without any FF/C effects would also require 88% collection efficiency but a pressure drop of 240 cm (94 in.) W.C. for collection of particles with a mass median aerodynamic diameter of 0.75 μmA and standard deviation of 2.5. The high energy scrubber would have to include the same mass transfer capability as the FF/C system and could have the same componente as the FF/C system except for the cooling tower and associated apparatus.

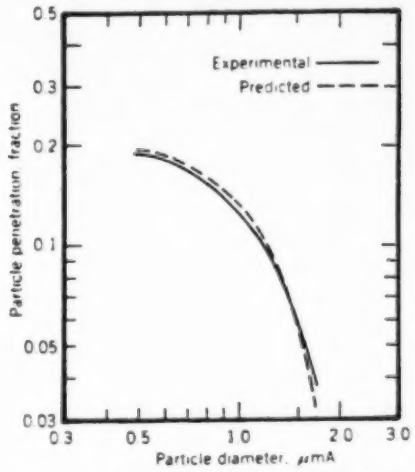

Figure 4. Particle penetration versus aerodynamic diameter for Run 64.

A cost comparison between the FF/C scrubber and the high energy scrubber is given in Table IV. The initial capital investment is lower for the FF/C system, and the annual power cost is less than the conventional system. After accounting for depreciation and all operating costs including power, the total annual cost of the FF/C system is about $10,000 less than the conventional high energy system at this particular source. The cost of electric power used was 0.045 ¢/kWh.

Conclusions

The following conclusions can be drawn from this study:

1. Demonstration plant performance was consistent with the results of previous studies on FF/C scrubbing.
2. A conventional high energy scrubbing system without any FF/C effects would require a pressure drop of about 250

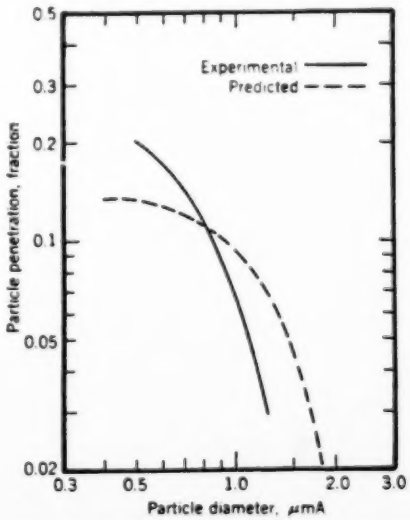

Figure 5. Particle penetration versus aerodynamic diameter for Run 74.

Table IV. Cost comparison for premium wire recovery.

Cost item[a]	Cost for FF/C	Cost for conventional
Total Capital Investment	$103,100	$111,240
Depreciation[b]	10,310	11,125
Maintenance	6,185	6,675
Water	180	180
Raw Materials	1,650	1,650
Power[c]	2,370	11,530
Total Annual Cost	$20,695	$31,160

[a] 4th quarter 1976.
[b] 10 years straight line.
[c] 0.045¢/kWh.

cm (98 in.) W.C. to give the same efficiency as the demonstration plant did at 68 cm (27 in.) W.C. pressure drop.

3. Particle number concentration and grown particle sizes are very important in FF/C scrubbing.
4. An improved and simplified design procedure gave performance predictions which were in good agreement with experimental results.
5. An FF/C scrubber capable of controlling No. 1 premium wire incineration from this source would cost $103,100 to install and would have a total annual cost of about $21,000 based on a 10 life depreciation and all operating charges.

Acknowledgment

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Abbreviations and Symbols

C' = Cunningham correction factor, dimensionless
d_p = particle diameter, μm
n_p = particle number concentration, no./cm^3
S.S. = stainless steel
σ_g = geometric standard deviation of particle size distribution
ρ_p = particle density, g/cm^3
μm = micrometer (micron)
μmA = aerodynamic diameter, $d_p(C'\rho_p)^{1/2}$, μm $(g/cm^3)^{1/2}$
W.C. = water column

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